TEXAS INSTRUMENTS

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Advanced Research Projects Agency (ARPA)
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ATTENTION: Mr. Donald C. Sharkus

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Sir:

Enclosure (1) is submitted in accordance with reference (a) requirements. If you require technical information concerning this submittal, please contact R. E. Terrill at (214) 995-1094. If you require contractual information, please contact Al Naylor at (214) 995-3200.

Sincerely,

Laura Harvey

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Data Manager

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LIQUEFIED METAL JET PROGRAM
AUTOMATION AND ROBOTICS
RESEARCH INSTITUTE (ARRI)

SPECIAL TECHNICAL REPORT

ENVIRONMENTAL IMPACT STUDY

Sponsored by:
Advanced Research Projects Agency (ARPA)
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Liquefied Metal Jet Program (LMJP)

ARPA Order No. 9328/03

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TEXAS INSTRUMENTS

ENVIRONMENTAL IMPACT STUDY FOR LIQUEFIED METAL JET TECHNOLOGY: AN ALTERNATIVE PRINTED CIRCUIT BOARD MANUFACTURING PROCESS

1.0 ABSTRACT

Department of Defense (DoD) agencies are major users of electronics and are responsible for much of the current printing wiring board (PWB) manufacturing. Current manufacturing of PWBs utilizes photolithography and chemical etchings which are subtractive processing techniques creating tons of hazardous waste materials and waste water each year. The current processing techniques apply photoresist to the surface of a copper clad board only to remove more than 90 percent of both copper and resist in the next phase of processing. The subtractive process is by design a wasteful processing technique. Current manufacturing processes limit the line size and spaces which determine the circuit density and number of PWB layers.

The proposed alternative manufacturing technology is Liquid Metal Jetting (LMJ). While offering significant reductions in hazardous waste produced and overall processing cost, LMJ can excel in one-of-a-kind and replication type PWB production. The proposed LMJ process can produce extremely fine PWB patterns with circuit lines much smaller than existing technologies. With a direct computer-aided design (CAD) interface, the LMJ process is especially compatible with one-of-a-kind and rapid prototyping applications. This just-in-time (JIT) fabrication and replication fits directly into DoD agency missions such as the deployment of facilities to support the line of battle.

This two-year study was a team effort among Texas Instruments (TI) Incorporated and the Automation & Robotics Research Institute of the University of Texas at Arlington (UTA/ARRI). Other participants included Sandia National Laboratories (SNL), Wright Laboratory (WL/MTE), and the Best Manufacturing Practices (BMP) program from the Office of the Assistant Secretary of the Navy (Research, Development and Acquisition). This study created a demonstrable prototype system capable of manufacturing PWBs via an additive process. The project was based on UTA/ARRI's current Solder Jet research program which has developed a proprietary system capable of printing very precise droplets of lead-based solder for electronic soldering applications.

The LMJ technology could impact every aspect of PWB manufacturing as the existing processing technologies for PWB manufacturing are in serious need of modification or replacement. The LMJ process is unique and represents one logical, cost effective, environmentally friendly method of PWB manufacturing. LMJ could impact new and future technology requirements such as ball grid arrays (BGAs), very fine pitch applications, and one-of-a-kind manufacturing. All PWB manufacturers including large, small, and prototype shops could use LMJ to reduce environment wastes.

2.0 EXECUTIVE SUMMARY

As an additive manufacturing process, LMJ will significantly reduce or eliminate the use of environmentally compromising processes and materials in the PWB manufacturing process. Each year, tons of electrochemically contaminated copper and lead dross will not be generated. Additional positive impacts include

the ability to quickly and economically manufacture one-of-a-kind PWBs and the rapid manufacture and replacement of damaged PWB boards and *in situ* modification of existing boards.

In this study, the environmental impact was evaluated if LMJ was used in the direct copper printing of circuit lines on PWB substrates and the direct printing of solder for tin/plate plating/pretinning. Assuming that the remaining LMJ technological problems could be resolved, LMJ technology could enable PWB fabricators to dramatically reduce by as much as 70 percent the quantity of chemicals used and hazardous waste generated in the production of PWBs. In addition, labor savings of 60 percent could also be realized through utilization of LMJ technology over conventional PWB technology. In the TI Austin facility alone, the estimated annual savings in the range of $20 million.

The impact to the DoD and the ecology from the LMJ process is expected to include:

- Elimination of subtractive copper etching process and many hazards from PWB manufacturing
- Elimination of all photolithography processing from PWB production
- Reduction or elimination of CFC and HCFC emissions as a result of PWB cleaning processes
- Reduction or elimination of lead use and emissions for lead solders.

The demonstration prototypes developed in this study have established the viability of LMJ technology as a significant improvement in PWB affordability, flexibility, and environmental concerns. The next step (i.e., study) is to further parameterize the process, complete the printing capability for the copper system and then convert the prototype into a robust, industrial hardened PWB process that can be used throughout the defense and commercial industrial base.

3.0 BACKGROUND

Problem Statement

Since 1994 the commercial value of PWBs has exceeded $8.3 billion (U.S.) annually. Existing technologies utilized in this extensive manufacturing and assembly of PWBs have not changed fundamentally in over forty years. PWB production still remains, for the most part, a plating and subsequent chemical removal process. Likewise, plating of multilayer vias, through holes and surface mount of components of PWBs continues to be based on the application of lead-based solders and various fixing compounds. These methods generate millions of pounds of copper, copper contaminated lead, and lead contaminated waste compounds every year. In addition, the flux and photolithographic chemical clean-up associated with the manufacture of PWBs generates approximately six billion gallons of waste water per year. Almost all flux and photolithography chemicals and approximately 80 percent of the copper is passed through the PWB production process as waste. This waste and inefficient material utilization with the attendant impact on environment and national productivity cannot be overcome without major modification in the current technologies of PWB manufacturing.

The continuous pressure toward miniaturization in most electronics manufacturing over the past four decades also is evident in PWB production. Current methods of PWB manufacturing appear to be reaching a limit

of diminishing returns in terms of smaller sizes with attendant increase in packaging densities. Issues which were of no consequence at larger sizes have now become the determining factors in the manufacture of PWBs. The general state-of-the-art for PWBs is about 10-mil pitch (i.e., 10-mil metal line with 10-mil space). As finer and finer pitches are required, a reduction of effort and cost does not presently appear feasible using current technology.

This study addresses the use of LMJ technology in an adaptation of current ink printing methods for PWB manufacturing. This novel technology is an adaptive process which will eliminate all photolithographic waste and most of the chemical removal waste and has the potential for producing even submicron line widths (which would reduce the current size by a factor of a 100). A further intrinsic advantage of the LMJ is the ability to produce PWBs JIT, and in variable-mix PWB batches down to one board at a time.

Comparison of Competing Technologies

The development of LMJ as an environmentally compatible process for PWB manufacturing and assembly is at the forefront of research concerns at the UTA/ARRI. UTA/ARRI's Solder Jet research team has developed a printing technology for the extremely precise application of lead-based solder. This technology is based on an adaptation of the industrial standard ink jet printing process. Existing support from the State of Texas, TI, Motorola, IBM, and Tandy has allowed UTA/ARRI to develop a major research program in this area. The Liquid Metal Jet systems under development at UTA/ARRI are capable of dispensing molten metal droplets (liquid copper and non-leaded-based solder) in the size range of 100 μm to 500 μm in diameter at temperatures in excess of 2300°F. The research progression for using ink jet technology to dispense liquid metals is shown in Figure 1.

The LMJ team has expanded existing process knowledge and nozzle design theory to include the precision application of extremely high temperature metals such as copper and non-lead-based solders. The proposed team has developed a LMJ printing process capable of printing extremely small droplets (100 mm to 1 mm) of liquid copper and non-lead-based solder. The approach selected in the LMJ study included the use of the UTA/ARRI proprietary printhead design. This approach removes the piezo-based temperature barrier allowing the extension of ink jet printing technology into the areas of higher metal (such as copper) melting temperatures.

Relevance to the Defense Mission

The defense industrial base has been identified as the single largest polluter in the United States. Defense contractors are under pressure to implement new environmentally conscious manufacturing processes in the production of defense weapon systems. Land, sea, air, and space electronic weapon systems, from hand-held communication equipment to smart weapons and satellite surveillance, rely heavily upon PWB technology. Researchers have not yet been able to identify an alternative affordable technology to replace PWBs, and DoD weapon systems will continue to be dependent upon PWBs for the foreseeable future. As a result, environmentally conscious methods of PWB fabrication and assembly are highly desirable if the DoD is to meet the defense industry environmental impact goals established by the President and the secretaries of the armed services.

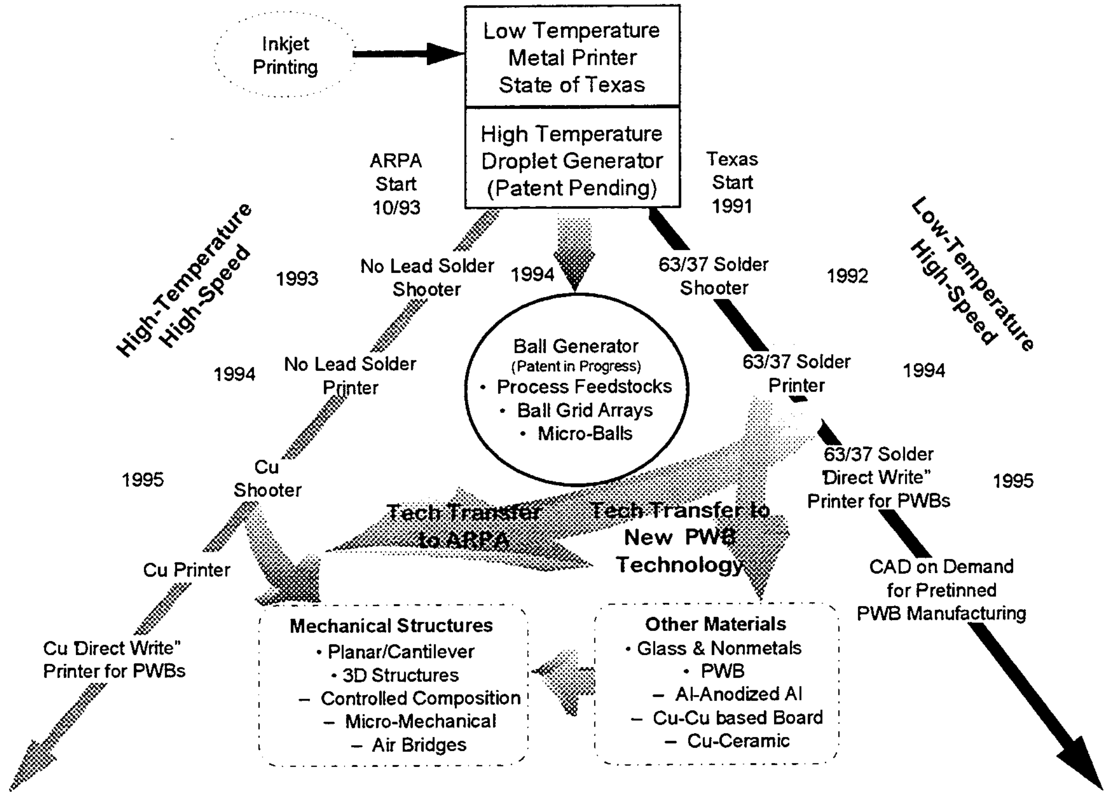

Figure 1. LMJ Research Progression

4.0 ENVIRONMENTAL STUDY

To illustrate the potential environmental benefits of LMJ, the research team used case study data compiled by TI during a sixteen week Industrial Modernization Incentives Program (IMIP) factory analysis of TI's Austin PWB fabrication facility for the U.S. Air Force. The IMIP was a rigorous cost and productivity analysis to highlight key processes for modernization. Data from the IMIP analysis was evaluated and combined with research data from this study. It was assumed that the remaining LMJ technological problems could be resolved.

The process chemical usage from TI Austin is summarized in Table 1. LMJ was assumed to modify or replace eight of the sixteen process steps. Steps 2 and 8 through 14 were affected. Table 1 illustrates the enormous advantages to be gained by implementing LMJ technology in PWB facilities. LMJ technology will enable PWB fabricators to reduce the quantity of chemicals used and hazardous waste generated in the production of PWBs by as much as 70 percent. In addition, labor savings of 60 percent can be realized through utilization of LMJ technology over conventional PWB technology. Nearly two million pounds of chemicals, in excess of two million square feet of photoresist film, and tens of millions of gallons of water per years can be saved at TI's PWB facility using LMJ technology.

A tangible example of the benefits of LMJ technology was developed with the TI Austin facility operations. By patterning circuits using LMJ techniques, large amounts of chemicals and solutions would be

eliminated. Table 1 shows the current methods of constructing a PWB (As Is Baseline), the proposed method to be using LMJ, and the amount of chemicals saved annually at TI by this change. The major reductions of waste copper, photoresist, acids and cleaners by implementing LMJ are substantial. Certain hazardous chemicals such as formaldehyde, now used in PWB manufacture, would be eliminated. In addition to the elimination of the materials listed, large volumes of water are consumed in the existing process, 78 million gallons annually at TI Austin. In the TI Austin facility the estimated annual savings is on the order of $20 million.

TABLE 1. ENVIRONMENTAL AND LABOR COMPARISON BETWEEN EXISTING TECHNOLOGY AND LMJ

STEP	EXISTING PWB PROCESS	EXISTING PWB PROCESS CHEMICALS	LMJ PROCESS	LMJ CHEMICAL AVOIDANCE VOLUME UNITS	EXISTING PWB PROCESS LABOR (NORMALIZED)	LMJ PROCESS/LABOR (NORMALIZED)
1	Layer Clean/ Coat Image	Resist Sulfuric Sodium Persulfate OS317		2,106,000 Ft^2 100,000 Lbs	5.26%	1.50%
2	Layer Dev/ Etch/Strip	Copper Hydrocholoric Soda Ash Hydrogen Peroxide OS Stripper Defoamer 754	Copper	80,000 Lbs 365,000 Lbs 46,000 Lbs 80,000 Lbs 10,000 Lbs 5,000 Lbs	2.26%	0.75%
3	Oxide Treat		Oxide Treat		6.77%	6.77%
4	Lam/Bond		Lam/Bond		8.27%	8.27%
5	Drill		Drill		7.52%	7.52%
6	Plasma Etchback		Plasma Etchback		4.51%	4.51%
7	Vapor Hone		Vapor Hone		1.50%	1.50%
8	Metallize	Formaldehyde Copper Palladium	Copper		7.52%	0.75%
9	Copper Plate	Sulfuric Nitric Acid Hydroxide Copper Anodes Liquid Copper Sulfate		100,000 Lbs 234,000 Lbs 90,000 Lbs 34,000 Lbs	7.25%	0%
10	Panel Image	Resist Soda Ash Sulfuric Pumice		421,000 Ft^2 incl #1 incl #1	4.51%	0%
11	Tin Lead Plate	Plultin LA Additive Fluroborate Acid Tin Lead Anodes Tin Lead Slats Microtech Acid Cleaner	Tin Lead	600 Lbs 26,000 Lbs 60,000 Lbs 2,200 Lbs 18,000 Lbs 1,200 Lbs	7.52%	0.75%
12	Strip/Etch	Potassium Hydroxide Ammonia Defoamer 754		 100,000 Lbs incl #2	7.52%	0%
13	Reflow	Flux Oil	Reflow	24,000 Lbs	8.27%	8.27%
14	Solder mask		Solder mask		9.02%	0%
15	Rout		Rout		7.52%	7.52%
16	Pack/Ship		Pack/Ship		0.75%	0.75%
				Total	100%	40.60%